Inclusion of Building Envelope Thermal Lag Effects in Linear Regression Models of Daily Basis Building Energy Use Data

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Background

Steady-state data-driven energy use models (daily data)

- Widely used for Measurement and Verification (M&V) of energy savings from energy conservation measures
- Suitable for simple energy performance analysis
- 24-hour cycle variations are averaged out in daily data.
  - The dominant driving terms of most buildings follow a 24 h cycle. (Rabl, 1992)

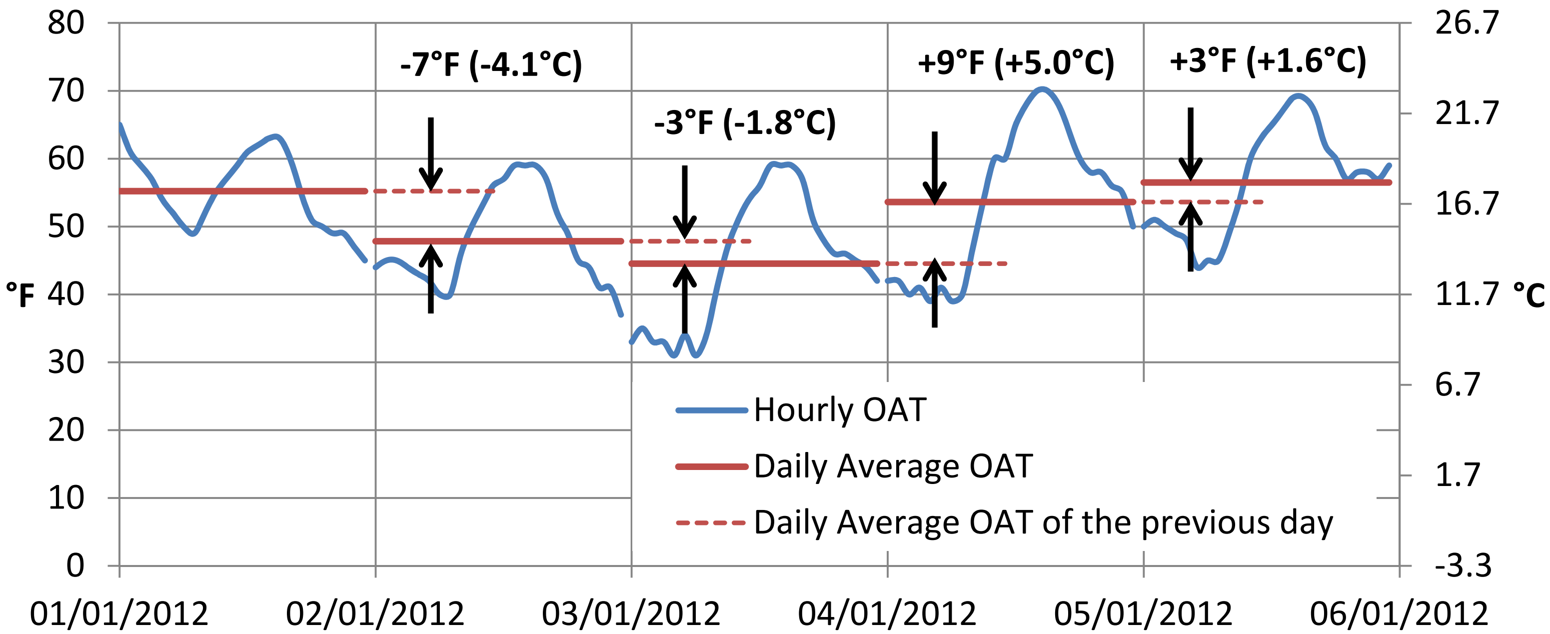
    solar irradiance, OA temperature, ventilation, occupancy level, lights and equipment loads, delayed loads due to thermal inertia
- Appropriateness of a steady-state approximation (Kissock 1993)
  - Net cooling energy time-constant for a building was estimated as 45 mins.
  - The system achieves 99.99% of its steady state after 24 hours.
- Transient effects from driving factors with lower frequency variations are treated as errors.

Background

Daily temperature differential: $T_{oa\text{-}diff}$ (Masuda and Claridge 2011)

- Difference of the daily average outside air dry-bulb temperature from the previous day's average
- $T_{oa\text{-}diff}$ variable is expected to pick up some effects of day-to-day temperature variation on the building load.

$$T_{oa-diff} = T_{oa,\,present\ day} - T_{oa,\,previous\ day}$$



Background

Steady-state multiple linear regression (MLR) model for Energy Balance variable (Masuda and Claridge, 2011)

- To obtain better models, 5 explanatory variables are included in Energy balance (E_{BL}) MLR models
  - Energy balance variable (Shao and Claridge, 2006) is evaluated from daily energy consumption of electricity, cooling, and heating.

$$E_{BL} = \text{Non}-\text{cooling electricity use} - \text{cooling energy use} + \text{heaitng energy use}$$
$$= -(Q_{air} + Q_{cond} + Q_{occ} + Q_{solar})$$

  - OA dry-bulb temperature (T_{oa}), humidity ratio (W_{oa}^{+}), solar irradiance (E_{Sol}), occupancy factor derived from the electricity use (D_{occ}), and daily temperature differential ($T_{oa\text{-}diff}$)
- Addition of $T_{oa\text{-}diff}$ variable decreased CV (=RMSE/mean) by 0.3%– 3.3% for the tested 10 buildings.
- $T_{oa\text{-}diff}$ had strong effects on E_{BL} (p-value < 0.0001) for all the tested buildings. The effect of $T_{oa\text{-}diff}$ was generally stronger than those for E_{Sol} and D_{occ}.

Questions

- What are we observing from this variable $T_{oa\text{-}diff}$?
  - Indoor temperatures for the tested buildings are roughly constant.
  - Is it from thermal inertia of the exterior walls?
- How does $T_{oa\text{-}diff}$ affect the parameter estimates of models?
- Does the variable improve energy use models also?

Test method

$T_{oa\text{-}diff}$ and thermal mass of the exterior walls

1. Generate hourly synthetic conduction load data Q_{cond}
   - Simple RC model with hourly Typical Meteorological Year weather data (TMY3)
   - Different wall constructions
   - Different thermal mass with constant U
   - Weather data from different locations
2. Calculate daily total Q_{cond}
3. Study regression results using the daily data

$$Q_{cond} = \beta_0 + \beta_1 T_{oa} + \varepsilon$$
$$Q_{cond} = \beta_0 + \beta_1 T_{oa} + \beta_2 T_{oa-diff} + \varepsilon$$

Test method

Simple RC model to generate synthetic conduction load data (Kusuda et al., 1971)

$$MC\frac{dT_w}{dt} = K_w(T_{oa} - T_w) - K_a(T_w - T_i)$$

and

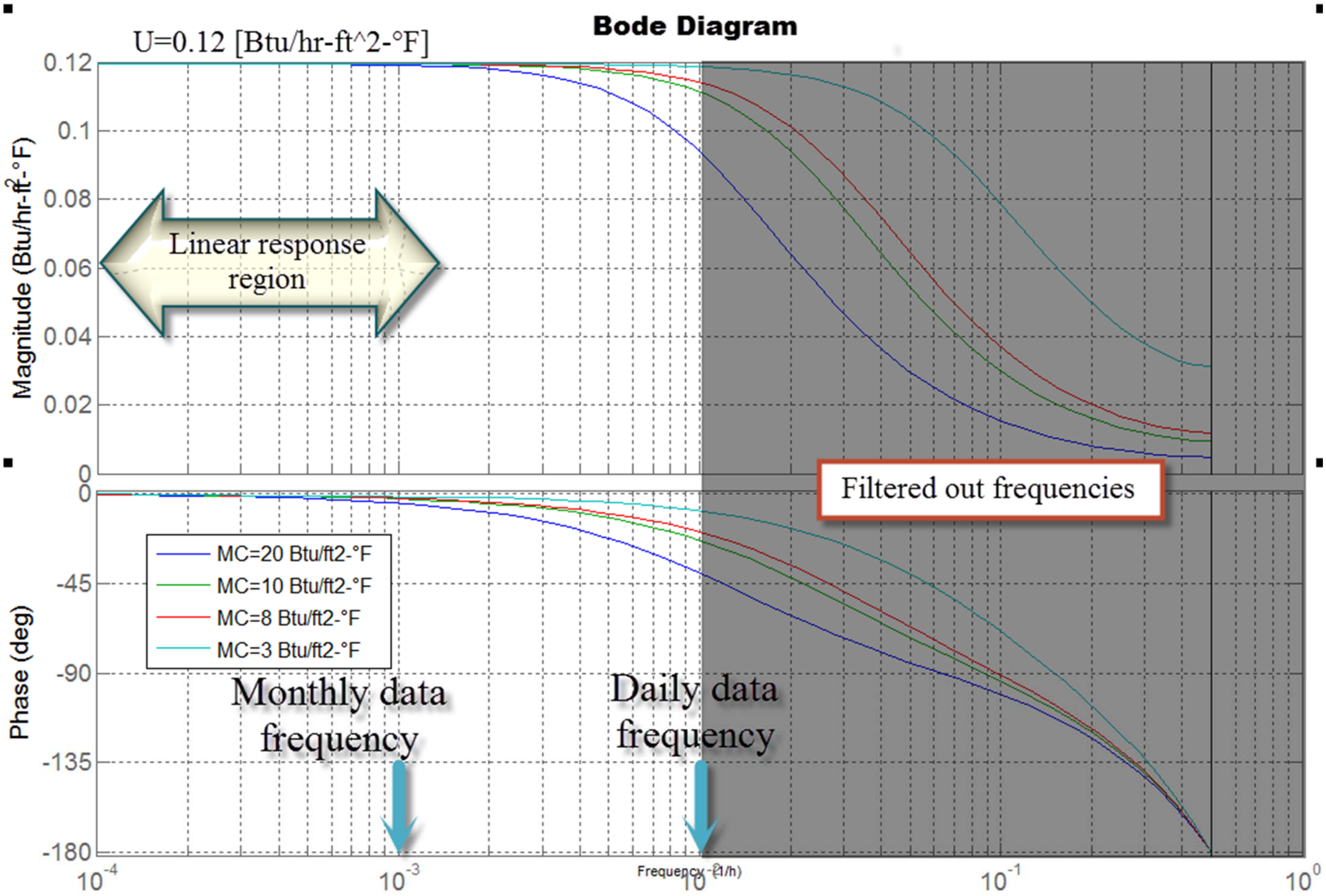
$$Q = K_a(T_i - T_w)$$

Modeled this equation with Simulink and directly input hourly T_{oa} data

Ti = 72°F (22.2°C) const.

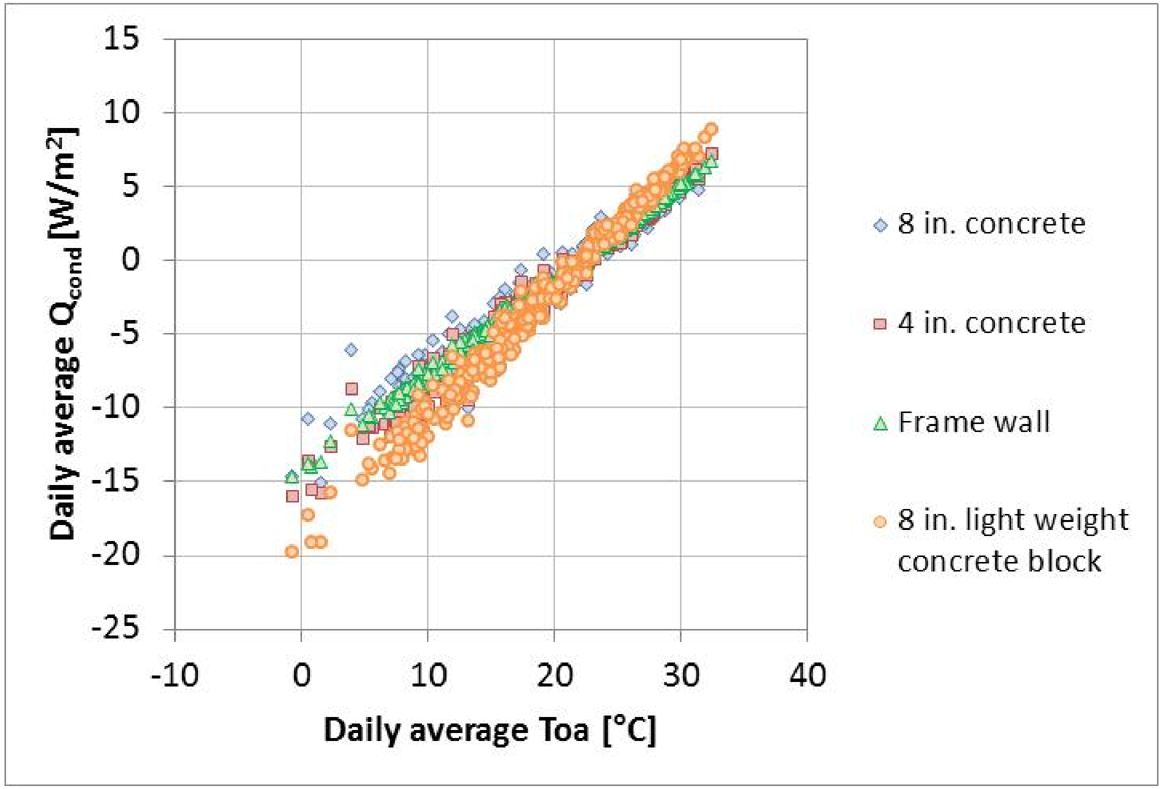
$Q_{cond} = -Q$

MC = thermal mass of the room shell
K_w = heat transfer factor for the exterior surface
K_a = heat transfer factor for the interior surface
T_w = temperature of the room shell
T_i = room air temperature
T_{oa} = outdoor air temperature
Q = energy requirement to maintain the room temperature



Bode Diagram
U=0.12 [Btu/hr-ft^2-°F]
Magnitude (Btu/hr-ft2-°F)
0.12
0.1
0.08
0.06
0.04
0.02
0
Linear response region
Filtered out frequencies
Phase (deg)
0
-45
-90
-135
-180
MC=20 Btu/ft2-°F
MC=10 Btu/ft2-°F
MC=8 Btu/ft2-°F
MC=3 Btu/ft2-°F
Monthly data frequency
Daily data frequency
Frequency (1/h)
10^-4
10^-3
10^-2
10^-1
10^0

Different wall constructions



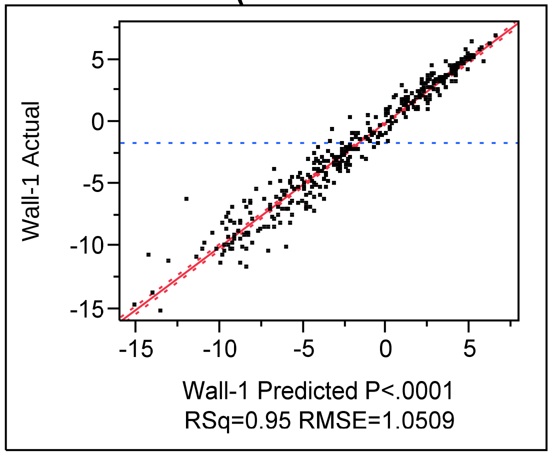
T_{oa} data: College Station, TX

Different wall constructions

Model-1: $Q_{cond} = \beta_0 + \beta_1 T_{oa} + \varepsilon$

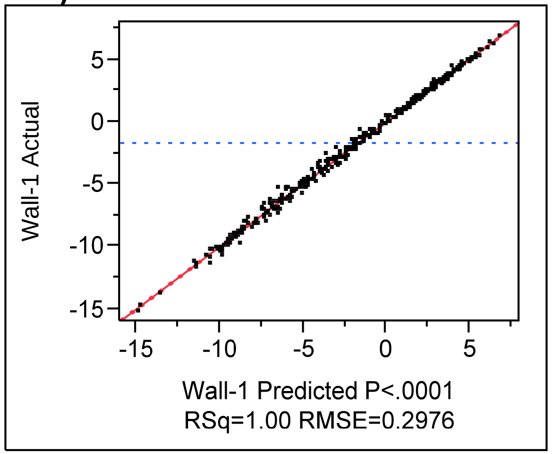
Model-2: $Q_{cond} = \beta_0 + \beta_1 T_{oa} + \beta_2 T_{oa-diff} + \varepsilon$

Heaviest wall (8 in. concrete with 2 in. insulation)

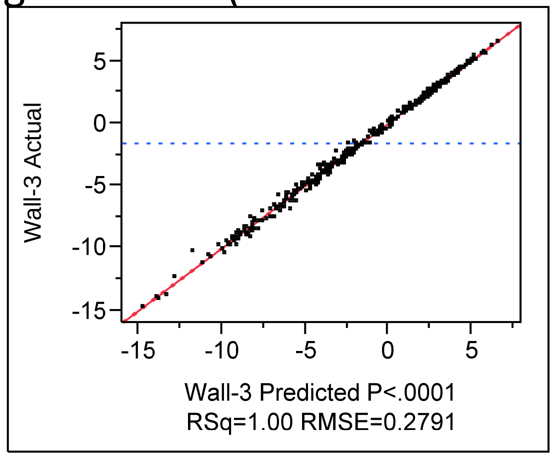


RMSE

-72%

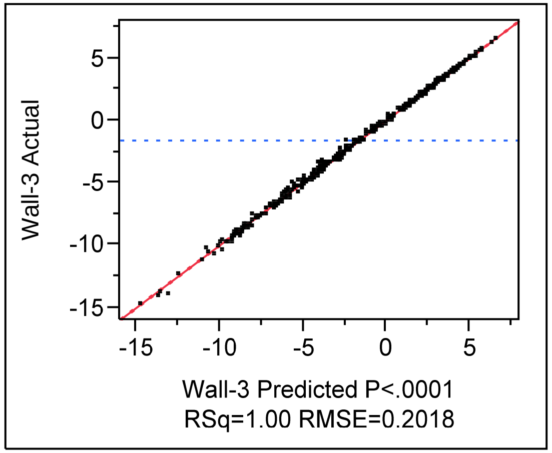


Lightest wall (frame wall with 2 in. insulation)

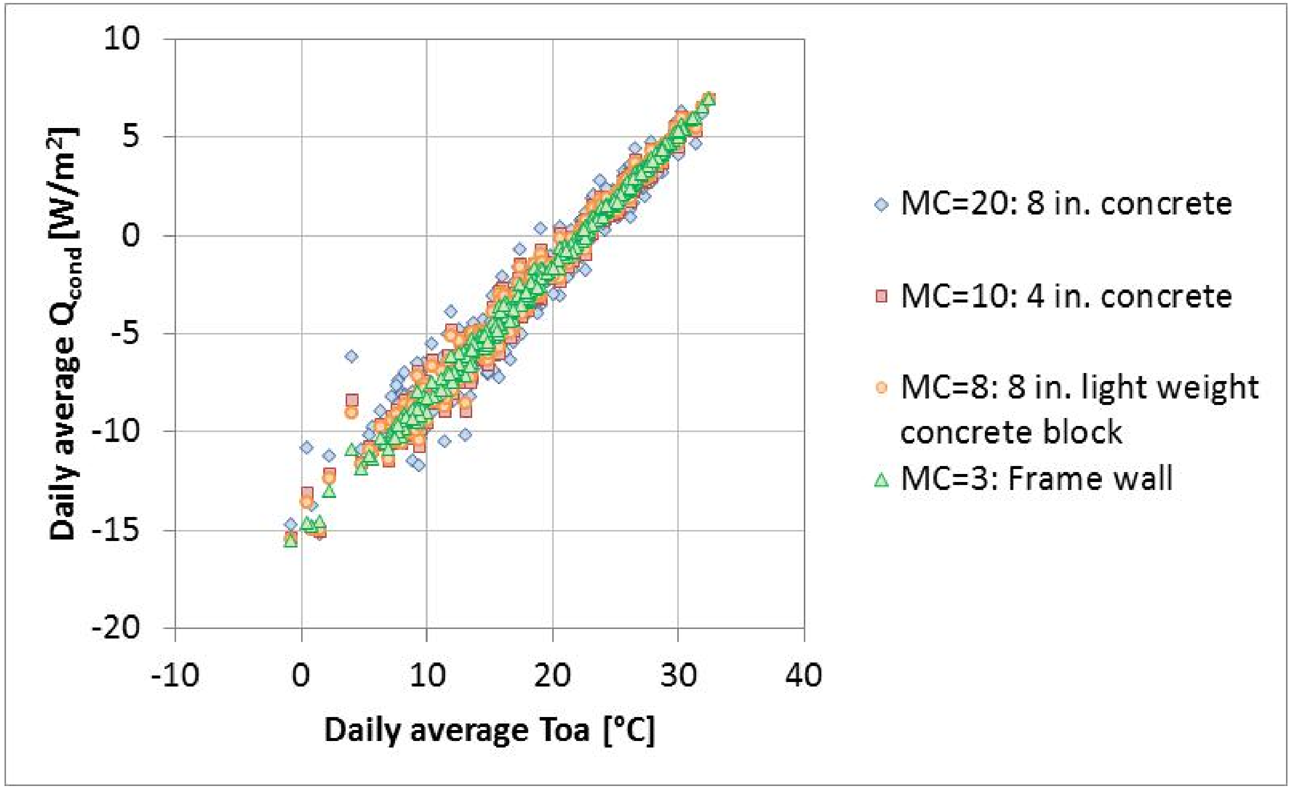


RMSE

-28%

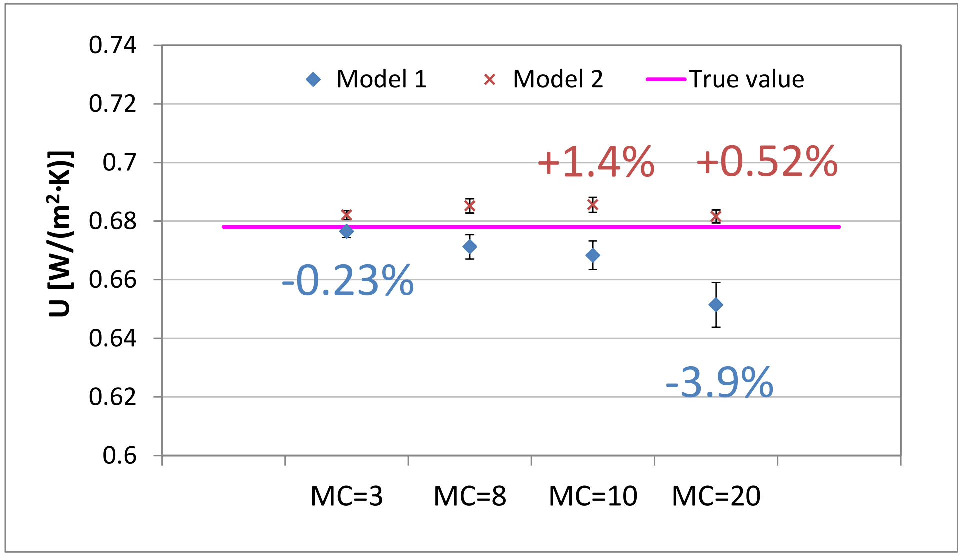


Different thermal mass with constant U



T_{oa} data: College Station, TX
U = 0.119 [Btu/hr-ft^2-°F]
(= 0.678 [W/(m^2·K)])

Different thermal mass with constant U

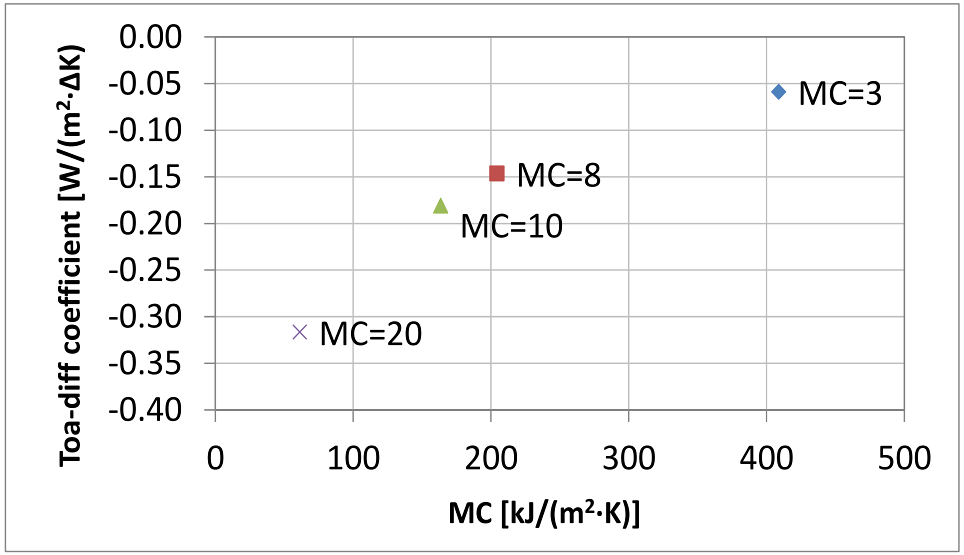


How accurately can U be estimated using regression analysis?

Model-1: $Q_{cond} = \beta_0 + \boldsymbol{\beta_1} T_{oa} + \varepsilon$

Model-2: $Q_{cond} = \beta_0 + \boldsymbol{\beta_1} T_{oa} + \beta_2 T_{oa-diff} + \varepsilon$

$$\mathrm{U}A = \hat{\beta}_1$$



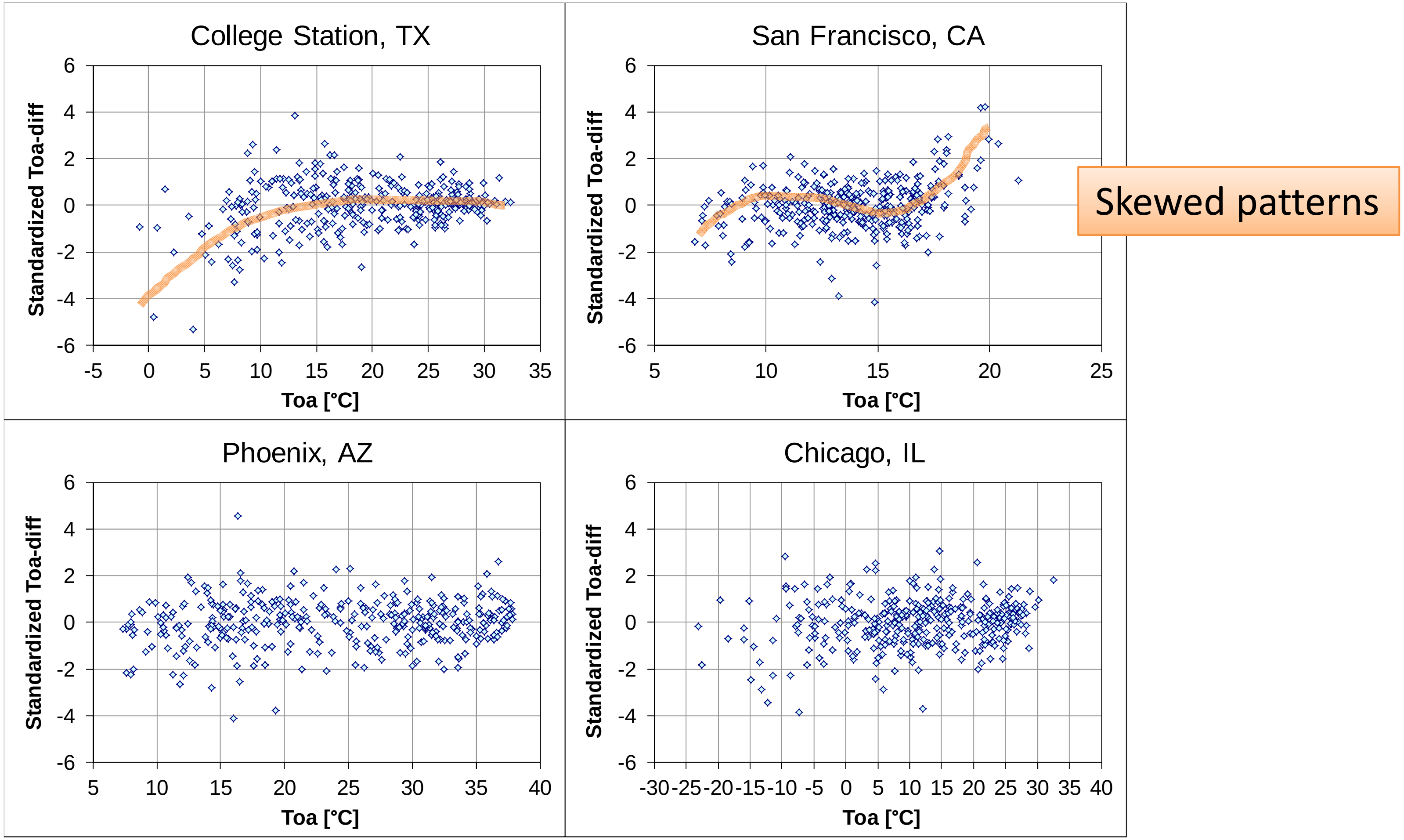
Toa-diff coefficient vs. wall thermal mass

Model-2: $Q_{cond} = \beta_0 + \beta_1 T_{oa} + \boldsymbol{\beta_2} T_{oa-diff} + \varepsilon$

Magnitude of the estimated $T_{oa\text{-}diff}$ coefficient tends to increase with the thermal mass

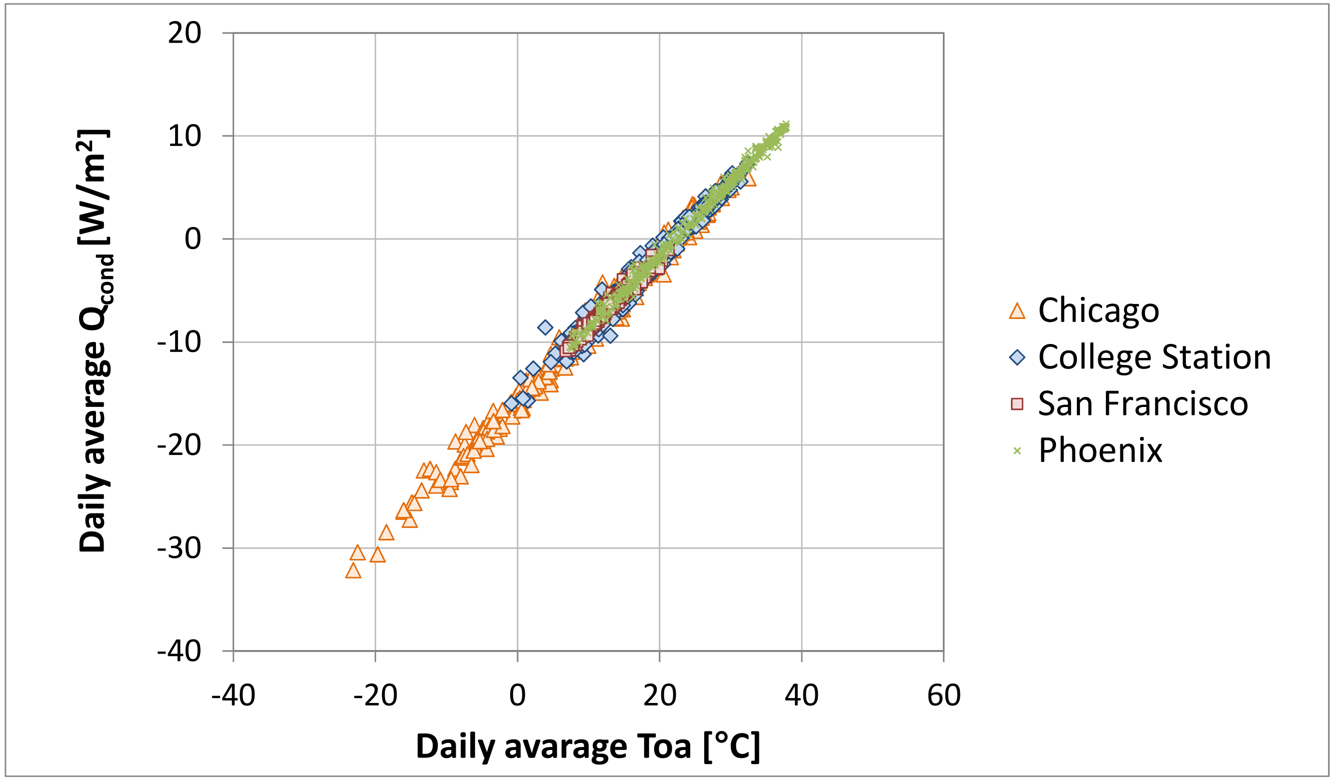
Different weather

Standardized $T_{oa\text{-}diff}$ = $T_{oa\text{-}diff}$ / standard deviation of $T_{oa\text{-}diff}$



The daily temperature differential is not always randomly distributed across the outside air temperature.

Different weather



T_{oa} data

College Station, TX

San Francisco, CA

Phoenix, AZ

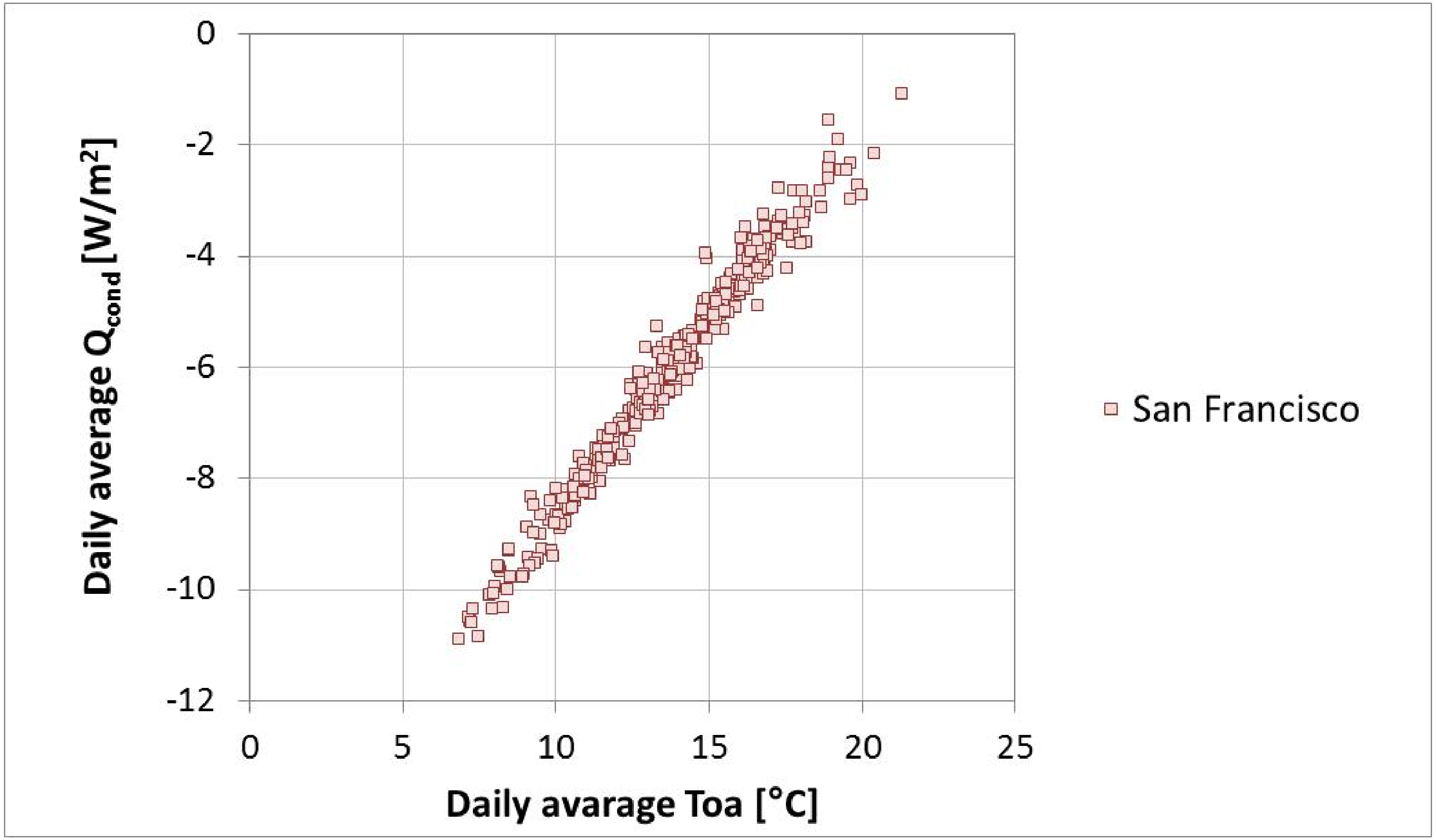
Chicago, IL

Wall construction

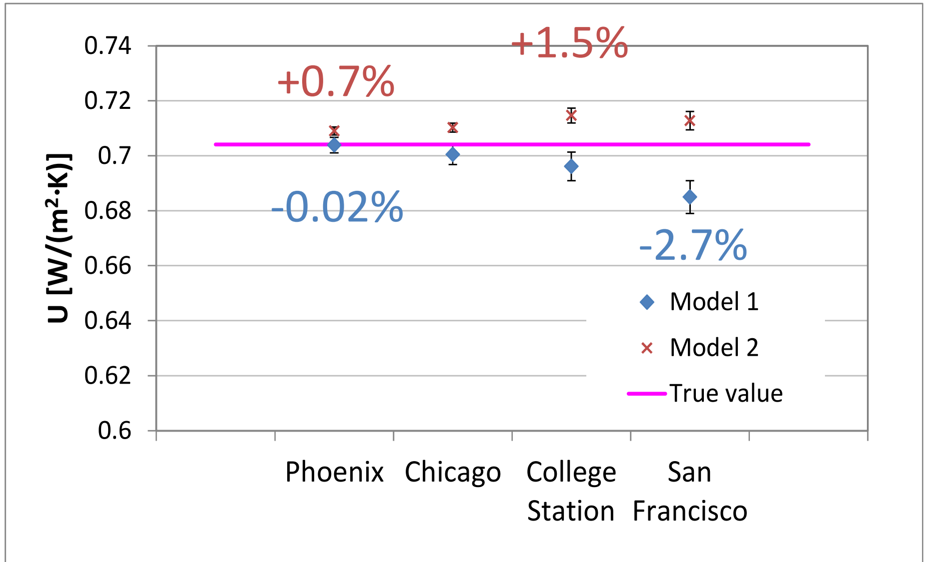
4 in. concrete and 2 in. insulation

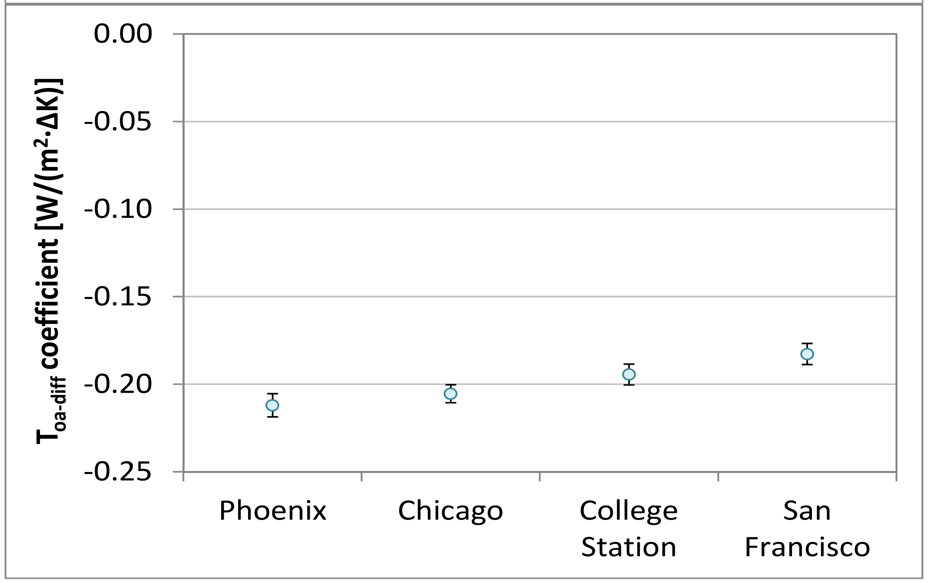
U = 0.124 [Btu/hr-ft^2-°F]

(= 0.707 [W/(m^2·K)])


0
-2
-4
-6
-8
-10
-12
Daily average Q_{cond} [W/m^2]
0
5
10
15
20
25
Daily avarage Toa [°C]
San Francisco

Different weather





Model-1: $Q_{cond} = \beta_0 + \boldsymbol{\beta_1} T_{oa} + \varepsilon$

Model-2: $Q_{cond} = \beta_0 + \boldsymbol{\beta_1} T_{oa} + \beta_2 T_{oa-diff} + \varepsilon$

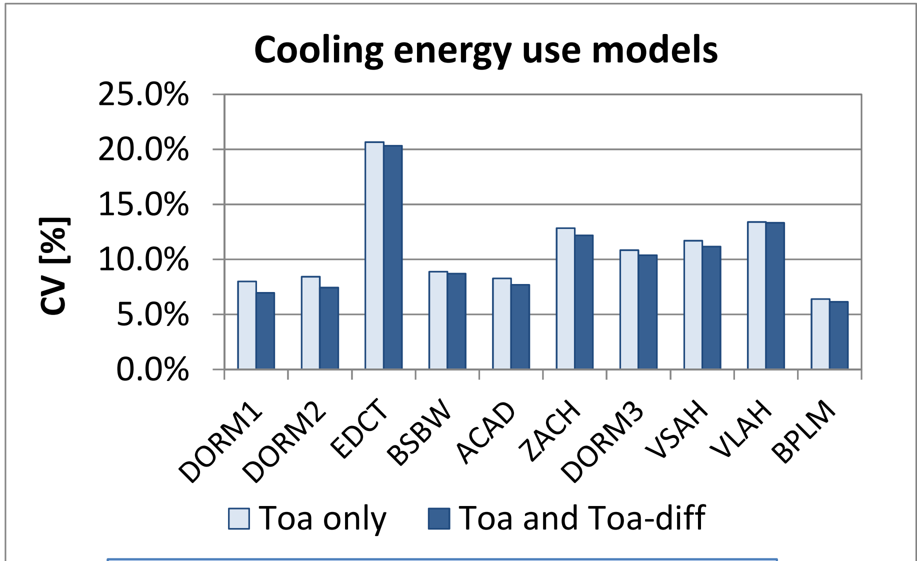
College Station and San Francisco have skewed patterns in the $T_{oa\text{-}diff}$ vs. T_{oa} plots.

Model-2: $Q_{cond} = \beta_0 + \beta_1 T_{oa} + \boldsymbol{\beta_2} T_{oa-diff} + \varepsilon$

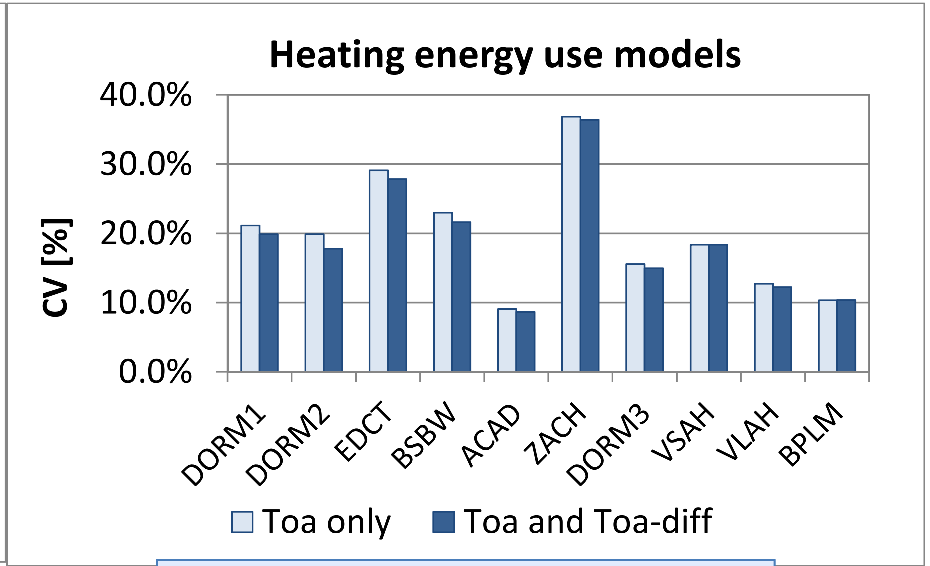
The effects of $T_{oa\text{-}diff}$ differ by the weather data.

Energy use models

- Cooling and heating energy use change point regression models
  - Model CVs are compared with and without the $T_{oa\text{-}diff}$ variable
  - Metered energy use data from 10 buildings in College Station, TX (same datasets as in Masuda and Claridge, 2011)
  - Models are improved in most cases by adding $T_{oa\text{-}diff}$ variable (10 out of 10 for cooling and 8 out of 10 for heating)
  - The sizes of the error decrease are small compared to E_{BL} models.



CV decreased by 0.1%–1.0%.



CV decreased by 0%–2.1%.

Summary

- Relationship of the daily temperature differential variable $T_{oa\text{-}diff}$ and thermal mass of building exterior walls has been examined.
- Under the tested conditions, the $T_{oa\text{-}diff}$ variable explains thermal inertia effect of exterior walls.
  - Thermal lag from temperature variations slower than 24 hour cycle appears.
- Inclusion of $T_{oa\text{-}diff}$ variable in regression models improves the stability of inverse estimation of the overall heat transfer coefficient U from the synthetic conduction loads.
  - Inverse estimation of U is more stable when $T_{oa\text{-}diff}$ is included in the models.
    - Error of U estimates: within 1.5% when $T_{oa\text{-}diff}$ is included, within 3.9% when not included.
  - It was observed that the effects of $T_{oa\text{-}diff}$ are present in the metered cooling and heating daily energy use. Energy use models can be improved by adding the $T_{oa\text{-}diff}$ variable. (Error decrease: 0.1%–1.0% for cooling and 0%–2.1% for heating)
- Advantages over time series models
  - The variable can be used for grouped data (weekday/weekend etc.)
  - Other parameters can be directly and physically interpreted.

References

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Kusuda, T., Tsuchiya, T., and Powell, F.J. (1971). Prediction of Indoor Temperature by Using Equivalent Thermal Mass Response Factors. Proceedings of the 5th Symposium on Temperature. Washington DC. June 21-24. 1971

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Wavelet decomposition of College Station, TX TMY3 temperature